

Three Active and Two Sterile Neutrinos in an E_6 Model of Diquark Baryogenesis

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Abstract

In the $U(1)_N$ extension of the supersymmetric standard model with E_6 particle content, the heavy singlet superfield N may decay into a quark and a diquark as well as an antiquark and an antidiquark, thus creating a baryon asymmetry of the Universe. We show how the three doublet and two singlet neutrinos in this model acquire mass from physics at the TeV scale without the benefit of using N as a heavy right-handed neutrino. Specifically, the active neutrinos get masses via the bilinear term $\mu L X^c$ which conserves R-parity, and via the nonzero masses of the sterile neutrinos. We predict fixed properties of the extra Z' boson, as well as the new lepton doublets X and X^c , and the observation of diquark resonances at hadron colliders in this scenario.

1 Introduction

There are two important issues regarding any extension beyond the minimal Standard Model (SM) of particle interactions. One is the implementation of a natural mechanism for small Majorana neutrino masses. This is highly desirable for understanding the current data on atmospheric and solar neutrino oscillations [1]. The other is the implementation of a natural mechanism for generating a baryon asymmetry of the Universe. With the addition of three heavy right-handed singlet neutrinos, both can be achieved. Unfortunately, this minimal extension of the SM is not subject to direct experimental verification at future colliders [2, 3].

If there is new physics at the TeV scale, it should be such that the above two properties are maintained. It has now been shown [4] that assuming the extended gauge symmetry to be a subgroup of the superstring-inspired E_6 , the success of leptogenesis requires it to be either $SU(3)_C \times SU(2)_L \times SU(2)'_R \times U(1)_{Y_L+Y'_R}$ [5, 6] or $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_N$ [7, 8]. Only these two gauge groups allow the superfield N^c to have zero quantum numbers with respect to all of their transformations. Hence N^c may become heavy and decouple from the low-energy phenomenology at the supersymmetry-breaking scale. Remarkably, these two subgroups are also the most favored gauge extensions of the SM as indicated [9] by the present neutral-current data from atomic parity violation [10] and precision measurements of the Z width. Depending on the choice of allowed terms in the superpotential, there are two versions of the $U(1)_N$ extension, i.e. Models 1 and 2 of Ref.[11]. Both use the decays of heavy right-handed neutrinos (corresponding to the superfield N^c) into leptons (or leptoquarks) to generate a lepton asymmetry in the early Universe [12] which gets converted into the present observed baryon asymmetry of the Universe through the electroweak sphalerons [13]. In any other extra $U(1)$ model, because its breaking at the TeV scale would introduce $B - L$ violating interactions at that scale, the coexistence of the $B + L$ violating sphalerons would

erase [14] any lepton or baryon asymmetry that may have been created at an earlier epoch of the Universe.

In this paper we present yet a third alternative which is an elaboration of Model 5 of Ref.[11] in the presence of $U(1)_N$. Here the heavy singlet superfield N^c which has $B - L = 1$ is considered to have $B = 1$ and $L = 0$ instead of $B = 0$ and $L = -1$ in the usual case. Since N^c is allowed to have a large Majorana mass in the $U(1)_N$ model, its decays (into a diquark and a quark as well as an antidiquark and an antiquark) may then generate a baryon asymmetry of the Universe. On the other hand, there is no coupling between N^c and ν , so there is no canonical seesaw mechanism available for m_ν . As shown previously [6, 7], there are in general 3 active and 2 sterile neutrinos in these E_6 models. They may acquire masses through their mixing with the extra neutral fermions (which are also leptons) at the TeV scale. Hence these neutrino masses are *not* related to the observed baryon asymmetry of the Universe. Instead, the active neutrino masses originate from: (i) the bilinear term μLX^c where X^c is a new heavy lepton doublet contained in the fundamental 27 representation of E_6 and which, in contrast to the bilinear R-parity breaking models [3], conserves R-parity; and (ii) the existence of massive sterile neutrinos. This means that we can also accommodate the LSND data [15] if confirmed. Furthermore, as we show below, the decays of the new heavy lepton doublets (X and X^c) of this model would allow us to map out (partially) the predicted 5×5 neutrino mass matrix.

2 Neutrino masses in the $U(1)_N$ model of diquark baryogenesis

The $U(1)_N$ model is defined [4, 7] by the charge assignments

$$Q_N = \sqrt{\frac{1}{40}}(6Y_L + T_{3R} - 9Y_R), \quad (1)$$

whereas the electric charge is given by

$$Q = T_{3L} + Y, \quad Y = Y_L + T_{3R} + Y_R, \quad (2)$$

under the usual decomposition of E_6 into $SU(3)_C \times SU(3)_L \times SU(3)_R$. The various matter superfields belonging to the fundamental $\underline{27}$ representation of E_6 transform under $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_N$ as follows:

$$Q = (u, d) \sim (3, 2, 1/6; 1/\sqrt{40}), \quad u^c \sim (3^*, 1, -2/3; 1/\sqrt{40}), \quad e^c \sim (1, 1, 1; 1/\sqrt{40}), \quad (3)$$

$$d^c \sim (3^*, 1, 1/3; 2/\sqrt{40}), \quad L = (\nu_e, e) \sim (1, 2, -1/2; 2/\sqrt{40}), \quad (4)$$

$$h \sim (3, 1, -1/3; -2/\sqrt{40}), \quad X^c = (E^c, N_E^c) \sim (1, 2, 1/2; -2/\sqrt{40}), \quad (5)$$

$$h^c \sim (3^*, 1, 1/3; -3/\sqrt{40}), \quad X = (\nu_E, E) \sim (1, 2, -1/2; -3/\sqrt{40}), \quad (6)$$

$$S \sim (1, 1, 0; 5/\sqrt{40}), \quad N^c \sim (1, 1, 0; 0). \quad (7)$$

The allowed terms in the superpotential are those which come from the decomposition of $\underline{27} \times \underline{27} \times \underline{27}$. There are eleven such terms. Five (Qu^cX^c , Qd^cX , Le^cX , Shh^c , SXX^c) are necessary for the usual SM particle masses as well as the new heavy particles, i.e. h , h^c , X , X^c . The other six (LN^cX^c , QLh^c , u^ce^ch , d^cN^ch , QQh , $u^cd^ch^c$) cannot *all* be there together because that would induce rapid proton decay. Thus in all E_6 models, a discrete symmetry (extension of R-parity) has to be imposed to get rid of some of the latter six terms. In the present case, we will adopt a $Z_2 \times Z_2$ discrete symmetry, which can be thought of as $(-1)^{3B} \times (-1)^L$, i.e. baryon parity and lepton parity, which are separately conserved. This choice is motivated by the behavior of the SM baryon and lepton numbers because they are indeed separately conserved in that case.

Let us now consider the simplest model, called Model A, resulting from the $Z_2 \times Z_2$ discrete symmetry. The first $Z_2 = (-1)^{3B}$ is required to prevent rapid proton decay and we impose it as follows,

$$Q, u^c, d^c, N^c \quad : \quad -1 \quad (8)$$

$$h, h^c, S, X, X^c, L, e^c \quad : \quad +1. \quad (9)$$

The allowed trilinear terms in the superpotential are now exactly as in Model 5 of Ref.[11]:

$$Qu^c X^c, Qd^c X, Le^c X, Shh^c, SXX^c, d^c N^c h, QQh, u^c d^c h^c, \quad (10)$$

together with the bilinear terms

$$LX^c, N^c N^c. \quad (11)$$

From the above, it is clear that h has $B = -2/3$ (antidiquark) and h^c has $B = 2/3$ (diquark). Therefore N^c is a baryon with $B = 1$ rather than a lepton.

The second discrete symmetry $Z_2 = (-1)^L$ is required to distinguish between the Higgs and matter supermultiplets. This is exactly analogous to the minimal supersymmetric standard model in which an appropriate R-parity must be imposed for the same reason. We impose the second Z_2 as follows,

$$L, e^c, S_{1,2}, X_{1,2}, X_{1,2}^c \quad : \quad -1 \quad (12)$$

$$Q, u^c, d^c, N^c, h, h^c, S_3, X_3, X_3^c \quad : \quad +1. \quad (13)$$

The allowed trilinear terms are now further restricted and the complete superpotential of Model A becomes

$$\begin{aligned} W = & \lambda_1^{ij} u_i^c Q_j X_3^c + \lambda_2^{ij} d_i^c Q_j X_3 + \lambda_3^{ij} e_i^c L_j X_3 + \lambda_4^{ab} S_3 X_a X_b^c + \lambda_4^{ab3} S_a X_b X_3^c + \lambda_4^{a3b} S_a X_3 X_b^c + \\ & \lambda_4^{333} S_3 X_3 X_3^c + \lambda_5^{ij} S_3 h_i h_j^c + \lambda_6^{ijk} u_i^c d_j^c h_k^c + \lambda_7^{ijk} h_i Q_j Q_k + \lambda_8^{ijk} d_i^c h_j N_k^c + \\ & \mu^{ia} L_i X_a^c + m_N^{ij} N_i^c N_j^c, \end{aligned} \quad (14)$$

where the flavor indices $i, j, k = 1, 2, 3$ run over all 3 flavors while $a, b = 1, 2$. For further reference we have explicitly written down the structure of the λ_4 terms. Eq. (14) implies that X_3, X_3^c, S_3 have $L = 0$ and are the Higgs superfields of this model; but because of the $LX_{1,2}^c$ term, $X_{1,2}^c$ have $L = -1$ and $X_{1,2}$ have $L = 1$. On the other hand, because of the $S_{1,2}X_{1,2}X_3^c$

and $S_{1,2}X_3X_{1,2}^c$ terms, L is both -1 and $+1$ for $S_{1,2}$. In other words, L is not conserved, only $(-1)^L$ is. Hence Majorana neutrino masses are expected in this model because they have even L parity. The model as it stands has no canonical seesaw neutrino mass because the LN^cX^c term is absent. (Hence it also has no provision for leptogenesis from the decays of N .) However, because of the $\mu LX_{1,2}^c$ term, 4 nonzero masses are still possible for the 3 active and 2 sterile neutrinos, as shown below.

Direct baryogenesis is the distinctive feature of this model. Because the heavy Majorana baryon N^c is allowed to have a large mass [$Q_N = 0$ for N^c as given in Eq. (7)], it may decay into the $B - L(= B) = -1$ final states $\tilde{h}d^c$, $h\tilde{d}^c$ via the λ_8 term in Eq. (14) as well as into their conjugate states with $B - L(= B) = 1$. Technically this mechanism of generating a $B - L$ asymmetry is completely analogous to the usual leptogenesis [12] except that a B asymmetry is created instead of an L asymmetry in the early Universe. Since the sphalerons violate $B + L$ but conserve $B - L$, this B asymmetry survives as a $B - L$ asymmetry in our present epoch and is observed as a baryon asymmetry. For the details of baryogenesis in E_6 models, see Ref.[4].

Let us now work out the details of how neutrinos become massive in Model A. As $U(1)_N$ is broken by the vacuum expectation value of the scalar component of S_3 , the corresponding gauge fermion pairs up with the S_3 fermionic component to form a massive Dirac particle. The fermionic components of $S_{1,2}$ remain massless and can be considered as sterile neutrinos [7]. The 9×9 mass matrix of the neutral fermions of this model with odd L parity, i.e. $\nu_{e,\mu,\tau}, S_{1,2}, \nu_{E_{1,2}}$ (from $X_{1,2}$), and $N_{E_{1,2}}^c$ (from $X_{1,2}^c$), is then given by

$$\mathcal{M} = \begin{bmatrix} 0 & 0 & 0 & \mu^{ia} \\ 0 & 0 & \lambda_4^{ab3}v_2 & \lambda_4^{a3b}v_1 \\ 0 & \lambda_4^{ba3}v_2 & 0 & M_a\delta_{ab} \\ (\mu^T)^{ai} & \lambda_4^{b3a}v_1 & M_a\delta_{ab} & 0 \end{bmatrix}, \quad (15)$$

where $v_1 = \langle \tilde{\nu}_{E_3} \rangle$, $v_2 = \langle \tilde{N}_{E_3}^c \rangle$, and $M_{1,2}$ are the mass eigenvalues of the $X_{1,2}X_{1,2}^c$ mass

matrix, proportional to $\langle \tilde{S}_3 \rangle$. It is clear from the above that 4 of the 9 fields are heavy with masses M_1, M_1, M_2, M_2 approximately, and that 4 others are light with seesaw masses inversely proportional to $M_{1,2}$. One neutrino, however, remains massless in this model. The 5×5 reduced mass matrix spanning the 3 active and 2 sterile neutrinos thus becomes

$$\mathcal{M}_\nu = \begin{bmatrix} 0 & \sum_c \mu^{ic} \lambda_4^{cb3} v_2 M_c^{-1} \\ \sum_c \lambda_4^{ac3} (\mu^T)^{cj} v_2 M_c^{-1} & \sum_c (\lambda_4^{ac3} \lambda_4^{c3b} + \lambda_4^{a3c} \lambda_4^{cb3}) v_1 v_2 M_c^{-1} \end{bmatrix}. \quad (16)$$

This shows explicitly that without the sterile neutrinos and without the bilinear term $\mu L X^c$, the active neutrinos themselves would be massless. Such a result has also been obtained recently in a very different model [16] of decaying sterile neutrinos from large extra dimensions. To obtain realistic neutrino masses, we note that the sterile neutrino masses may be of order 1 eV, and the off-diagonal entries in Eq. (16) of order 0.1 to 0.01 eV, then the active neutrino masses may be of order 10^{-2} to 10^{-4} eV.

3 Related phenomenology at colliders

We start our discussion regarding the structure of the neutrino mass matrix of Eq. (15) with three comments. First, the new heavy supefields $N_{1,2,3}^c$ do not contribute to Eq. (15). Thus the observed baryon asymmetry of the Universe, created via the λ_8 terms of Eq. (14), is not related in any way to the measured neutrino masses. Secondly, the mass matrix of Eq. (15) involves only *leptons*; no superpartners such as gauginos and Higgsinos are there. Thus, in spite of the presence of the μ entries from the bilinear $L X^c$ term, R-parity is conserved here. Third, the Yukawa coupling matrices λ_4 should be nonvanishing. The matrix λ_4^{3ab} which gives masses to the new leptons X, X^c can be chosen to be diagonal without loss of generality. The matrices λ_4^{ab3} and λ_4^{a3b} provide the mass terms $S \nu_E$ and $S N_E^c$, respectively, which must also be nonzero. Otherwise, all neutrinos would be massless as seen from Eq. (16).

Because the neutrino masses come entirely from new physics at the TeV scale, our model

has a good chance of getting tested at future collider experiments. The first issue to be determined is the existence of the sterile neutrinos. As $S_{1,2}$ have gauge couplings only to Z' , the invisible width of Z' is predicted to have the property

$$\Gamma(Z' \rightarrow \nu\bar{\nu} + S\bar{S}) = \left(\frac{62}{15}\right) \Gamma(Z' \rightarrow l^-l^+), \quad (17)$$

which should distinguish it from other Z' models. Also, neutrino oscillations between the 3 active and 2 sterile neutrinos are possible and *natural* in our model, so the LSND data can be accommodated. But even if the LSND results turn out to be erroneous, it is still possible that future long-baseline experiments and neutrino factories may see the conversion to sterile neutrinos at some different Δm^2 .

Another prediction of our model is the existence of the two heavy lepton doublets $X = (\nu_E, E)$ and $X^c = (E^c, N_E^c)$ which are almost degenerate in mass. Once produced, these new heavy particles may decay via gauge and Yukawa interactions. Because of the $S_{1,2}$ mixings with the heavy neutral leptons ν_E, N_E^c , the gauge interactions induce the decays

$$\begin{aligned} E_{1,2} &\rightarrow W^- S_{1,2}, & E_{1,2}^c &\rightarrow W^+ S_{1,2}, \\ \nu_{E_{1,2}} &\rightarrow Z S_{1,2}, & N_{E_{1,2}}^c &\rightarrow Z S_{1,2}. \end{aligned} \quad (18)$$

In principle, these decay processes measure directly the corresponding neutrino mixing angles in Eq. (15) which are predicted to be of order $\sim \mu/M$. On the other hand, the Yukawa couplings λ_4 in Eq. (14) give rise directly to the competing decays

$$\begin{aligned} E_{1,2} &\rightarrow H^- S_{1,2}, & E_{1,2}^c &\rightarrow H^+ S_{1,2}, \\ \nu_{E_{1,2}} &\rightarrow H^0 S_{1,2}, & N_{E_{1,2}}^c &\rightarrow H^0 S_{1,2}, \end{aligned} \quad (19)$$

where the physical charged Higgs boson $H^\pm(H^0)$ is a mixture of $\tilde{E}_3(\tilde{\nu}_{E_3})$ and $\tilde{E}_3^c(\tilde{N}_{E_3}^c)$. In our model, to get the correct order of magnitude for the neutrino masses, we estimate $\mu/M \sim 10^{-6}$ while $\lambda_4 \sim 10^{-5}$. Therefore the latter decays should be dominant. Notice

however that because the different sterile neutrino final states cannot be distinguished from each other, the structure of λ_4 couplings cannot be determined from these decays.

From the experimental point of view, decay modes of X, X^c with charged leptons in the final state offer much better signals for testing our model. Because the bilinear term LX^c mixes the known charged leptons with the new heavy charged leptons, the decays

$$N_{E_a}^c \rightarrow W^- e_i^c, \quad E_a^c \rightarrow Z e_i^c, \quad (20)$$

should occur. These are proportional to μ^{ia}/M_a . Hence the ratio of the branching fractions of the decays (20) over (19) is predicted to be $(\mu^{ia}/(\sum \lambda_4)M)^2 \sim 10^{-2}$. If 1% precision will be achieved in determining these branching fractions, one should then be able to obtain the structure of μ^{ia} for all $i = e, \mu, \tau$ and $a = 1, 2$. In this respect, our proposal is similar to that of Ref.[3].

Let us assume now that all λ_4 couplings are diagonal and equal. In that case, the measured $\mu^{ia}/\sum \lambda_4$ determines the flavor structure of the neutrino masses according to the 5×5 neutrino mass matrix of Eq. (16). This might be a crude approximation but it allows us to test our neutrino mass matrix up to an overall scale, which must then be determined from other neutrino experiments.

We finish this Section with a comment on the hadron-collider phenomenology. Our model necessarily predicts the existence of diquark superfields h, h^c with masses of order $M_{Z'}$. Perhaps the most distinctive experimental signatures are then s-channel diquark \tilde{h} and \tilde{h}^c resonances at hadron colliders. At the LHC, the initial state from 2 valence quarks carries $B = 2/3$, hence a diquark resonance may occur without suppression. This allows us to test the existence of \tilde{h} and \tilde{h}^c to about 5 TeV [17].

4 Model B

An important variation of our basic model, called Model B, can be obtained by choosing $N_{1,2}^c$ to have $(-1, +1)$ under $Z_2 \times Z_2$ as in Model A, but N_3^c is assigned $(+1, -1)$ instead. The decays of $N_{1,2}^c$ will again generate a baryon asymmetry. [Note that the condition of CP violation requires at least two such heavy superfields.] But now N_3^c is a lepton and the allowed term $LN_3^c X_3^c$ enables one linear combination of ν_e , ν_μ , and ν_τ to acquire a canonical seesaw mass. This is an excellent opportunity for choosing $\nu_\mu \cos \theta + \nu_\tau \sin \theta$ to be massive with θ near $\pi/4$ for maximal mixing to explain the atmospheric neutrino data. The other 2 active neutrinos will both become massive from Eq. (16) as before. This may provide a rationale for having one active neutrino mass much larger than the other two, and allow all 3 active neutrinos to be massive instead of only 2 as in Model A.

As an illustration, let

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2} & -1/2 & 1/2 \\ 1/\sqrt{2} & 1/2 & -1/2 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}, \quad (21)$$

and consider the following 5×5 neutrino mass matrix in the basis $(\nu_{1,2,3}, S_{1,2})$:

$$\mathcal{M}_\nu = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \mu_1 & \mu_2 \\ 0 & 0 & m_3 & 0 & 0 \\ 0 & \mu_1 & 0 & 0 & M \\ 0 & \mu_2 & 0 & M & 0 \end{bmatrix}. \quad (22)$$

Let $m_3 \sim 0.05$ eV and choose

$$m_2 \sim \frac{2\mu_1\mu_2}{M} \sim 3 \times 10^{-3} \text{ eV}, \quad (23)$$

then we have maximal atmospheric neutrino oscillations with $\Delta m^2 \sim 2.5 \times 10^{-3} \text{ eV}^2$ and maximal solar neutrino oscillations with $\Delta m^2 \sim 10^{-5} \text{ eV}^2$. If LSND data are also to be

explained, then we can set $M \sim 2$ eV, $\mu_1 \sim 0.5$ eV, $\mu_2 \sim 6 \times 10^{-3}$ eV, so that

$$P_{\mu e} \sim \frac{1}{4} \left(\frac{\mu_1^2 + \mu_2^2}{M^2} \right)^2 \sim 10^{-3}, \quad (24)$$

in agreement with experiment.

5 Conclusions

In the context of superstring-inspired E_6 extensions of the supersymmetric SM, we have shown how the three active and two sterile neutrinos obtain realistic masses in two $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_N$ models of diquark baryogenesis. This extra $U(1)_N$ is favored over other extra $U(1)$ models by recent neutral-current data from atomic parity violation and the invisible Z width. In our scenario, neutrino masses originate from new physics at the TeV scale and are not related to the baryogenesis parameters at a very high scale. The active neutrinos acquire masses from the R-parity conserving bilinear superpotential term $\mu L X^c$ and nonzero sterile neutrino masses. Some of the neutrino mass matrix entries can be directly tested with the decays of the new heavy lepton doublets X and X^c at future collider experiments. We also predict the fixed properties of the extra Z' boson, the necessary existence of two sterile neutrinos, and the observation of diquark resonances at the LHC or Tevatron.

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References

- [1] Y. Fukuda *et al.*, Super-Kamiokande Collaboration, Phys. Rev. Lett. **81**, 1158 (1998); **82**, 1810, 2430 (1999); Phys. Lett. **B433**, 9 (1998); **B467**, 185 (1999); Phys. Rev. Lett. **82**, 2644 (1999).
- [2] Three recent proposals regarding the origin of neutrino mass but not baryogenesis are exceptions to this general rule: the models with enlarged Higgs sector by E. Ma, M. Raidal, and U. Sarkar, Phys. Rev. Lett. **85**, 3769 (2000) and by E. Ma, hep-ph/0011121, and the model of bilinear R-parity breaking in Ref. [3].
- [3] W. Porod, M. Hirsch, J. Romao, and J.W.F. Valle, hep-ph/0011248, hep-ph/0009128.
- [4] T. Hambye, E. Ma, M. Raidal, and U. Sarkar, hep-ph/0011197.
- [5] E. Ma, Phys. Rev. **D36**, 274 (1987); K. S. Babu, X.-G. He, and E. Ma, Phys. Rev. **D36**, 878 (1987).
- [6] E. Ma, Phys. Rev. **D62**, 093022 (2000).
- [7] E. Ma, Phys. Lett. **B380**, 286 (1996).
- [8] E. Keith and E. Ma, Phys. Rev. **D54**, 3587 (1996).
- [9] J. Erler and P. Langacker, Phys. Rev. Lett. **84**, 212 (2000).
- [10] S. C. Bennett and C. E. Wieman, Phys. Rev. Lett. **82**, 2484 (1999).
- [11] E. Ma, Phys. Rev. Lett. **60**, 1363 (1988).
- [12] M. Fukugita and T. Yanagida, Phys. Lett. **174B**, 45 (1986).
- [13] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, Phys. Lett. **155B**, 36 (1985).

- [14] B. A. Campbell, S. Davidson, J. E. Ellis, and K. Olive, Phys. Lett. **B256**, 457 (1991);
W. Fischler, G. F. Giudice, R. G. Leigh, and S. Paban, *ibid.* **258**, 45 (1991); H. Dreiner
and G. G. Ross, Nucl. Phys. **B410**, 188 (1993); J. M. Cline, K. Kainulainen, and K.
A. Olive, Phys. Rev. **D49**, 6394 (1994); E. Ma, M. Raidal, and U. Sarkar, Phys. Lett.
B460, 359 (1999).
- [15] C. Athanassopoulos *et al.*, Phys. Rev. Lett. **75**, 2650 (1995); **77**, 3082 (1996); **81**, 1774
(1998).
- [16] E. Ma, G. Rajasekaran, and U. Sarkar, Phys. Lett. **B495**, 363 (2000).
- [17] E. Ma, M. Raidal, and U. Sarkar, Eur. Phys. J. **C8**, 301 (1999).